Saskatchewan

A D F

Agriculture Development Fund

FINAL REPORT

VERTICAL ALLIANCE IN AGRICULTURE RESEARCH: CANOLA AN EXAMPLE OF SUCCESS

19950334

Funded by
The Agriculture Development Fund
February 2001

Prepared by: University of Saskatchewan

SAF
Saskatchewan Agriculture & Food

Adding value to agriculture...through research and development

101-04716/

The Economics of CWRS Wheat Research in Western Canada 1961-1998

Richard Gray and Stavroula Malla

2000

Department of Agricultural Economics
University of Saskatchewan
Saskatoon, Sask. S7N 5A8

A Report prepared for Agricultural Development Fund,
Saskatchewan Agriculture and Food

The Economics of CWRS Wheat Research in Western Canada 1961-1998

By

R. S. Gray and S. Malla

Abstract

This report examines the nature of the economic return to wheat research in western Canada for the period 1961 to 1998. Until 1998 wheat research funding was dominated by the public sector, in sharp contrast to canola research, which was 80% private by 1998. The question addressed in this study is whether the lack of private investment reflects a lower social rate of return to wheat research. The hexaploid genetic structure of wheat, the short growing season, and high protein requirements have created significant challenges for wheat breeders. Despite these challenges the yield data shows that significant yield improvements have been achieved over the past 40 years with the introduction of a few "breakthrough" wheat varieties, with relatively few gains made between these innovations. The sporatic nature of the yield increases and the time series properties of the data prevented a reliable econometric estimate of an expenditure/change-in-yield relationship. The average return to wheat research was calculated using various lag structures, depreciation rates, and yield maintenance functions. The results indicate that under a wide range of assumptions the real rate of return to wheat research has been 17% to over 36% per year, which are well above market rates of return. At an 8% real discount rate the present value of research has exceeded the present value of research expenditure by a four-to-one ratio. These results indicate that CWRS wheat research has been a public investment with a high rate of return. The lack of interest of the private sector in wheat breeding reflects the inability of breeders to capture the benefits rather that a lack of social return. As part of a larger body of research this study indicates that a single public research policy for all crops may not be appropriate.

Executive Summary

Wheat research is still dominated by public institutions, and the vast majority of the acreage is planted to publicly developed varieties. Only very recently has the private sector begun to significantly invest in wheat research, with an interest in developing herbicide-tolerant varieties. The recent research activity in the canola industry stands in sharp contrast to the wheat industry. Since 1985, there has been a massive influx of private research investment into canola.

This report examines the nature of the return to wheat research. In doing so it will address the question of whether the lack of private research in wheat reflects low expected social returns or the lack of effective intellectual property rights. By comparing these results to canola research, the paper will also draws some general conclusions about the appropriate role for government in crop research.

An economic model is presented in Section 2.0 that describes how incomplete property rights over crop varieties can reduce the private incentives for yield-improving crop research. The model also shows that, when more complete property rights are in place, government subsidies can create an overinvestment in research.

A summary of the recent changes in the canola industry and recent estimates of the return to canola research are reported in Section 3.0. The results indicate that with the massive influx of private research the return to canola research has fallen and recently has approached market rates of return.

Section 4.0 contains a brief literature review of previous studies that have examined the rate of return to wheat research. This review indicates that these studies have consistently shown a high historic rate of return to wheat research.

Section 5.0 describes some of the unique challenges faced by wheat breeders. This includes a description of genetics of the wheat and the difficulty the hexaploid structure poses for breeders. The challenges created by the short growing season and high protein requirements are also discussed.

Section 6.0 describes the data used to estimate the rate of return to wheat research. The yield data shows yield improvements have been made with the introduction of a few "breakthrough" wheat varieties, with relatively few gains made between these innovations.

Section 7.0 describes in detail the attempt made to econometrically estimate the relationship between research expenditures and the change in yield. Unfortunately, the sporatic nature of the yield increases and the time series properties of the data prevented a reliable econometric estimate of an expenditure / change-in-yield relationship.

Section 8.0 estimates the average return to wheat research using the 1960 to 1998 yield data. In the calculations, various lag structures, depreciation rates and yield maintenance

functions are used. A calculation based on econometrically estimated parameters is used for the sake of comparison. The results indicate that under a very broad set of assumptions the real rate of return to wheat research has been 17% to over 36% per year, which is well above market rates of return. At an 8% real discount rate the present value of research has exceeded the present value of research expenditure by a four-to-one ratio. As expected, knowledge deprecation rates decrease the internal rate of return. Even modest amounts of yield maintenance have large positive impacts on the estimated rate of return. A decade-by-decade breakdown shows no evidence of a decline in the rate of return.

Section 9.0 concludes the report with a discussion of the policy implications of the results. The results show that wheat remains a public investment with a high rate of return. The lack of interest by the private sector reflects the inability of breeders to capture the benefits rather that a lack of social return. The large acreage and volume of production suggests that wheat should continue to be an important part of research strategy. The comparison of these results to those derived for canola research in another study indicates that a common public research policy for all crops may be inappropriate.

Table of Contents

1.0 Introduction 1

2.0 An Economic Model to Examine Institutions and the Return to Research 3

3.0 The Development of Canola and the Rates of Return to Research 6

4.0 The Returns to Wheat Research - Literature Review 13

5.0 Physical Constraints in Wheat Yield Increase in Canada 18

6.0 Estimating the returns to research - Description of the Data 24

7.0 Econometric Analysis 30

8.0 The Returns to Wheat Research 34

9.0 Policy lessons 43

Literature Cited 46

The Economics of Wheat Research in Western Canada

1.0 Introduction

Wheat research has a very prestigious history in western Canada. The development of hard, high protein, early maturing spring wheat varieties combined with decreased transport costs allowed the settlement of the large area of short grass prairie in western Canada at the beginning of the century. Throughout the century, new higher yielding varieties were bred that retained the milling quality characteristics while providing greater resistance to pests and disease. These Canadian Western Red Spring (CWRS) wheat varieties are recognized in many markets as the best in the world for bread making. While the proportion of area planted to wheat has decreased somewhat, CWRS wheat has remained the most popular crop choice of producers for the past century in western Canada. The wheat varieties that created and maintained this industry were developed through publicly funded research activity.

Clearly, another success story in Canadian breeding has been the development of canola, which is now the second most valuable crop in Canada. The early development of edible rapeseed was the result of a modestly funded program of public research that began in the late 1950's. Much of the research activity to change the characteristics of the oil and meal of rapeseed was in response to findings that erucic acid in the oil and glucosynalates in the meal could adversely affect human and animal health respectively. Addressing these quality problems became the primary objective of the Rapeseed Association of Canada, formed in 1967, which instituted a check-off on processing and exports to enhance the public research program. In 1974 the first varieties low in both erucic acid and glucosynalates were introduced. Soon afterward, the canola trademark was established and the crop became established in the world oilseed markets as a healthy vegetable oil. With the help of the new Canola Council of Canada canola became the second most valuable crop in western Canada. Thanks to the relatively rapid transformation of the crop from an insignificant industrial oil to a major world oilseed crop, canola became

known as Canada's Cinderella crop. Throughout this period of growth, the research was dominated by researchers at public institutions working with the coordination of the industry association (Malla and Gray, 1999).

Recent research activity in the canola industry stands in sharp contrast to that in the wheat industry. Since 1985, there has been a massive influx of private research investment into canola. In 1997, private research into canola had grown to approximately $85 million per year, or 80% of total research expenditures (Malla and Gray, 1999). In 1997, 95% of the varieties planted were developed in private research programs. There has not has not been a flood of private research into CWRS wheat. Wheat research is still dominated by public institutions, and the vast majority of the acreage is planted to publicly developed varieties. Only very recently has the private sector begun to significantly invest in wheat research with an interest in developing herbicide-tolerant varieties.

This paper examines the nature of the return to wheat research. In doing so it will address the question of whether the lack of private research into wheat reflects low expected social returns or the lack of effective intellectual property rights. By comparing these results to canola research, the paper will also draw some general conclusions about the appropriate role for government in crop research. If canola is the Cinderella crop, attracting a great deal of private and government support, then wheat is one of the ordinary "stepsisters". Governments and the private sector have moved away from wheat toward canola and other crops. Is this because of a decline in the expected return to wheat research? Has the privatization of canola research improved efficiency in this sector while the stagnant institutions in the wheat sector have led to low rates of return to wheat research? An alternative hypothesis, which is described in this report, is that canola has attracted so much of the public and private investment that wheat is now a better public research investment.

This report is organized in nine sections. Section 2.0 creates an economic framework to examine research policy. To contrast the wheat sector with the canola sector, Section 3.0

briefly summarizes the recent analysis of the returns to canola research. Section 4.0 reviews previous estimates of the returns to wheat research. Section 5.0 describes the genetic structure of wheat and outlines some of the constraints faced by wheat breeders. A description of the data used to estimate the social return to wheat research is provided in Section 6.0. The attempts to econometrically estimate the relationship between research expenditures and yield increases are reported in Section 7.0. The estimated the rates of return to wheat research are described and reported in Section 8.0. Section 9.0 concludes the report with a description of policy lessons that can be gleaned from these results, plus a list of unanswered questions and a prescription for further research.

2.0 An Economic Model to Examine Institutions and the Return to Research[1]

In the absence of enforceable property rights, many of the products of research can be copied or reproduced. In the case of wheat, a crop grown from a new variety can be retained and used as seed for future crops. This creates a "public good" market failure that reduces the market demand for new varieties, which results in underinvestment in research activities. As shown in Figure 1, in the absence of complete property rights the private marginal benefit (*MBp*) that can be captured from the marketplace is less than the public or social benefits (*MBs*) of the research. A private research firm will equate the marginal cost (*MC*) of doing research with the private demand (or private marginal benefit) for the research and produce a quantity of research *Qp*. At this amount of research the social marginal benefit of research is far greater than the marginal cost of doing research. In this case, the marketplace fails to produce the socially optimal amount of research *Qs*, where the marginal cost of research is equal marginal social benefit. If the government provides a quantity of research *Qg – Qp*, this research creates a social benefit equal to the additional area under the social benefit curve while incurring costs equal to the much small area under the marginal cost curve. In this instance there is a high rate of

return to public research, which has been found in many empirical studies. This illustration may characterize the situation for canola research up to the mid-1980s and for wheat research throughout the 20th century.

Government has also addressed the incomplete set of property rights for research goods by assisting private firms doing research. This assistance has come in many forms. Research tax credits have been used in many countries, and more recently grants have provided money to match private expenditures on research (Alston, Norton and Pardey, 1997). Infrastructure has also been provided at a reduced cost in many jurisdictions. Indirect support from the public sector has also come in the form of the public education of research scientists and the free provision of the output of public research. This public assistance to private research has lowered the private cost of doing research, allowing the private sector to do more.

In Canada the public sector has always provided some direct support for private sector research into canola. Investment tax credits and infrastructure grants have existed for some time (Malla, Gray and Philips, 1998). Since 1995 the government has also offered matching investment initiatives (MII), which match private research expenditure in approved projects. This has allowed the private sector to play a greater role in research provision. In Figure 1 this is equivalent to lowering the marginal cost of private research to *MCp'*, which, in the absence of complete property rights, moves the private investment toward the socially optimal level *Qs* to a level of *Qp'*.

Recently, governments, and to some extent the private sector, have addressed the "public good" market failure in research by establishing effective property rights over the products of research. As outlined by Malla, Gray and Philips (1998) the assignment of intellectual property rights provided some of the added ability to capture value from research. The adoption of Plant Breeder's Rights in Canada forbade the sale of registered varieties without royalty payments. This assignment followed a number of milestones,

---

[1] The economic framework presented here is common to the framework and description presented in Malla and Gray (1999).

including the US Patent Office decision of 1985 to grant patents for whole plants. Many of the seeds produced during the 1990s had very specific attributes. Herbicide-tolerant canola requires the use of a specific herbicide in order to be useful. Similarly, canola with particular oil characteristics needed specialized processing and marketing in order to be viable. The development of hybrid varieties has given private firms a greater ability to capture value from their genetic material. The first hybrid variety was introduced in 1998. These varieties, although often protected with Plant Breeder's Rights and production contracts, do not require the enforcement of contracts to maintain control over the use of the genetics.

The establishment of enforceable property rights has the effect of moving the private marginal benefit (market demand) curve toward the social demand curve. As was discussed earlier, this has had the effect of increasing the demand for private research and the amount of private research provided by the private sector, thus partially addressing the market failure. In the absence of government support for research, this moves the private investment from *Qp* to *Qp"* in Figure 1. The establishment of property rights changes the optimal role for government. If government provides support for private research, once property rights are established this further increases the private incentive to do research. If the property rights are nearly complete and research support is significant, the private sector can provide more research than is socially desirable, as represented by point *Qp** in Figure 1. Thus, a correction of the public good failure combined with the subsidization of research costs can result in excessive research.

A few final points apparent in Figure 1 are worthy of note: 1) The highest benefit-to-cost ratio, which will generate the highest IRR, will be at some level of research less than the social optimum. 2) The socially optimal quantity research occurs where the marginal social benefit is equal to the marginal social cost. At this point total net benefits of research are maximized. Additional research beyond this point is socially wasteful, costing more on the margin than what is produced. 3) At excessive levels of research (anything more than *Qs* but less than the *Qx* in Figure 1) the total benefits can still be greater than total costs, and the IRR can still be above market rates. Importantly, a

positive overall return to research, or an IRR greater than market rates, does not imply that more research is socially desirable – rather, it suggests that the research program taken as whole has produced net benefits.

In summary, the simple economic model presented in Figures 1 illustrates several important concepts for research policy. The first is that, in the absence of enforceable property rights, the private sector will underinvest in research, creating a role for government in addressing the research shortage. Second, the assignment of property rights to research products can increase the amount of private investment toward the socially optimal amount. Third, if enforceable property rights have been established, the subsidization of private research could lead to socially wasteful overinvestment in research. Finally, assessments of total research benefits or the rates of return on total investment are not good indicators of whether more research is socially desirable.

3.0 The Development of Canola and the Rates of Return to Research

Canola is a good example of how research and development can improve the comparative advantage of an industry. A brief description of the industry development is found in Malla, Gray and Phillips (1998), and a more detailed description can be found in Kneen (1992). In the late 1950s rapeseed was minor crop in Canada that was used to make lubricant. By the 1980s, genetic, agronomic and processing research had transformed rapeseed into canola, a new crop that contained premium edible oil and a protein meal used for livestock feed. In the 1990s canola became the dominant crop in the black soil zone of the prairies, and a large processing industry had been built around it. In the past few years biotechnology has been used to develop transgenic herbicide-tolerant varieties and hybrid varieties that have been widely adopted by Canadian producers. Throughout this forty-year period of development, research has been an important catalyst for growth in the industry.

The funding of canola research in Canada has undergone many changes since its inception in the mid-1950s, when Agriculture Canada began a program to improve rapeseed processing methods. Over time, research has shifted from a modest public research program to a large research industry dominated by private sector participation. In 1970, 83% of research spending was public by funded. Ten years later, the percentage of public versus private research investment was 63% vs. 38% respectively. By 1997 the private sector's share had grown to 80% of the total (Canola Research Survey 1997). This funding shift is evident in the registration of new varieties. Prior to 1973 all varieties were public, while in the 1990-98 period 86% of the varieties were private (Canola Council of Canada 1998; Nagy and Furtan 1977; and Prairie Pools Inc. 1977 - 1992). This large shift in emphasis from public to private research is due to the large increase in private sector investment rather than a reduction in public research.

The change in the private funding of research has coincided with a change in the ownership of the property rights for the products of research and implicitly who benefits from the resulting returns to the investment. In 1987, virtually all of the canola varieties were open-pollinated and non-transgenic, and were not protected by Plant Breeder's Rights until 1990. This meant that virtually all of the acreage was grown without a production agreement, giving producers the right to retain production for future seed use and to sell non-registered seed to their neighbours. In contrast, by 1998, over one half of the acreage was planted to herbicide-tolerant (HT) varieties, where producers were required to sign a technology agreement or to purchase a specific herbicide. An estimated 30% of the acreage was seeded to hybrid varieties (Canola Council of Canada 1998) and much of the remaining acreage was seeded to varieties with Plant Breeder's Rights. These changes have put plant breeders in a far better position to capture value from genetic innovation.

Previous research has shown very high rates of return for canola research. The evaluation of public investment in canola research and development (R&D) was first published in 1977 by Nagy and Furtan. For the period 1960–1974 they calculated the internal rate of return (IRR) from improved yield research to be 101% per year. Ulrich, Furtan and

Downey (1984) updated the estimates of IRR in canola research for period 1951 to 1982 and calculated the IRR from improved yield research to be 51%. Ulrich and Furtan (1985) incorporated trade effects and found the estimated Canadian IRR from higher yielding varieties to be 50%.

Malla and Gray (1999) estimated the social return from the yield-increasing research using econometric estimates of the yield increase due to research expenditure applied to the historical production of canola. The regression results were used to predict the amount of yield increase due to research expenditure in each year. As an approximation, it was assumed that the additional yield due to genetic improvement came at no farmer resource cost and thus benefits are in direct proportion to revenue each year.[2] Annual research benefits in 1997 dollars were estimated by multiplying the quantity of canola seed (production) to the price of canola seed, and deflating by the consumer price index.[3]

The present value of research benefits were estimated by first calculating all future yield increases due to the yield increases in a particular year. This uses the notion described by Alston et al. that there is a built-upon stock of knowledge. This calculation was made using various rates of depreciation. These future yield increases were then applied to the revenue in each future year to calculate the future benefits. For 1997 and beyond it was assumed that 1997 revenue would continue indefinitely. Once the future stream of benefits was calculated this is then brought back to the present value in the year of introduction using a discount rate.

---

2 This is consistent with the treatment in the research plots where additional yield is measured with no additional use of crop inputs. There would be additional costs for harvesting and transport to the elevator, which are small per tonne so are not accounted for in our analysis.

3 The price of canola seed in Canada was obtained from Saskatchewan Agriculture and Food, *Agricultural Statistics 1997*. The price of canola seed was the Saskatchewan farm price in Canadian dollars per metric tone. The data for the consumer price index (CPI) was obtained from Statistics Canada, Direct Cansim Time Series: CPI and All Goods for Canada (1998). Finally, the quantity of canola production was obtained from Statistics Canada, Direct Cansim Time Series: Canola-Rapeseed/production, metric tonnes, canola-Canada, (1998).

The present value of costs for varieties grown in year t were calculated from the present value in year t of the weighted expenditures lagged by the gestation period and the adoption curve. The Net Present Value (NPV) of research is calculated from the difference between the present value of the benefits and the cost of the research using a range of depreciation and real discount rates.

The NPV results are reported in Table 1. What is most striking is that for each of the scenarios the NPV peaks in the 1980s and declines thereafter. For instance, with 5% depreciation and a 6% real discount rate, the increase in the research expenditures resulted in an increase in net present value from $41 million in 1971 to a peak of $88 million in 1983, which then began to decline as the increase in expenditures exceeded the growth in benefits. By 1997 the net present value of annual yield increase had declined to $25 million.

Table 2 shows the estimated IRR for the change in yield increases for the years 1970 - 1997, under different assumptions about deprecation rates and lag structures. The first four columns show the IRR from the regression results with a four-year gestation lag and 0%, 1%, 5% and 10% depreciation rates respectively. Not surprisingly, the IRR is lower with higher deprecation rates because the investment is not a durable. The last column of Table 4 shows the IRR with a one-year gestation period. As expected, this increases the IRR and illustrates once again that the IRR can be sensitive to assumptions about the gestation lag. What is most striking in this table is the general decline in the IRR as the level of investment has increased. While the IRR was clearly excessive in the early 1970s it had declined to market levels for the varieties introduced the mid-1990s.

Malla and Gray concluded that although many biotechnologies became predominant during the 1980s the declining NPV and IRR provides little support to the notion that biotech has led to significant increases in the social returns to research. The authors did acknowledge the research produced other benefits not measured as a yield increase in 1997 about 35% of area was sown to herbicide-tolerant varieties. Yet, given the very

recent introduction of herbicide-tolerant varieties, this phenomena does not explain the decline in the NPV in varieties released prior to 1996.

The increase in the level of expenditures and the declining IRR, approaching market rates, suggests that the assignment of property rights and matching grants has corrected the public good market failure. These rates of return would suggest an overinvestment in the sector, resulting in low private and social IRR for investment. The decline in the NPV of research as expenditure increases is consistent with moving beyond the optimal amount of research.

Figure 2 shows the IRR with 1% and 5% depreciation rates. One interesting feature of these series is the increase in the rate of return in the late 1970s, when canola acreage surged in response to growing on farm wheat stocks brought about by grain transportation constraints. Note, however, that revenue during the mid-1990s was near record levels, and despite this the rate of return is low.

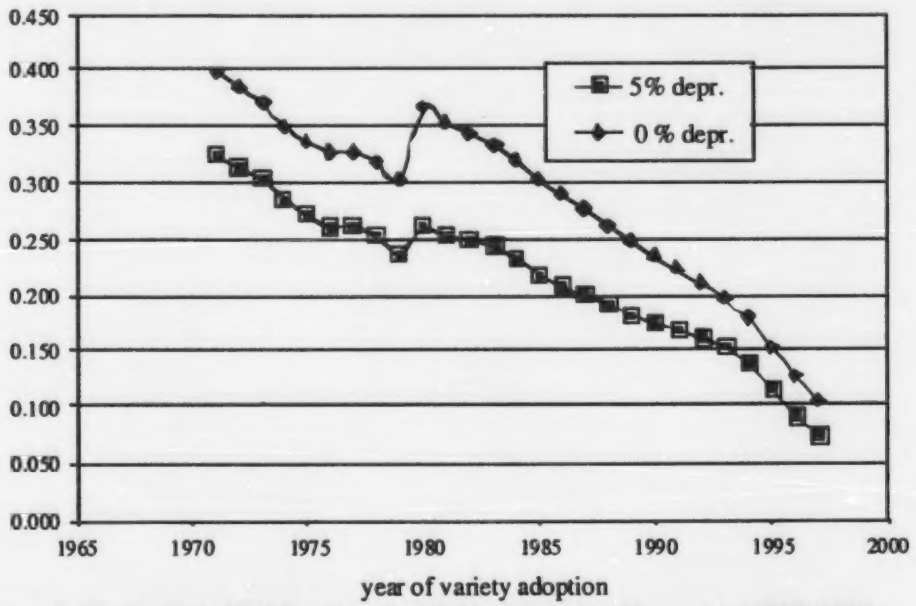

Figure 2: Estimated IRR for Canola Yield-Increasing Research (1967-1993)

TABLE 1: Net Present Value For Yield Increasing Canola Research

scenario	A	B	C	D	E	F
Depreciation	**0.01**	**0.05**	**0.01**	**0.05**	**0.01**	**0.05**
Real discount rate	**0.03**	**0.03**	**0.06**	**0.06**	**0.09**	**0.09**
YEAR of Yield Change						
	Net present Value (Millions of 1997 dollars)					
1971	66.8	44.8	63.2	41.8	59.4	38.6
1972	71.2	48.2	67.1	44.8	62.9	41.2
1973	76.7	52.5	72.2	48.7	67.4	44.6
1974	80.4	55.1	75.3	50.7	69.9	46.0
1975	85.7	58.1	79.9	53.1	73.8	47.7
1976	92.3	61.6	85.9	56.1	79.0	50.0
1977	101.2	68.0	94.2	62.0	86.8	55.4
1978	104.4	69.7	97.1	63.3	89.2	56.3
1979	103.0	66.3	95.3	59.6	86.9	52.1
1980	295.4	107.8	198.0	86.8	153.7	71.0
1981	294.4	107.5	194.6	85.3	149.2	68.6
1982	297.4	110.2	194.6	86.6	147.7	69.0
1983	300.5	113.0	194.4	87.8	146.0	69.1
1984	302.3	112.8	191.8	85.8	141.4	65.8
1985	302.7	111.7	187.7	82.5	135.2	61.0
1986	304.5	112.7	185.2	81.3	130.5	58.2
1987	306.4	115.0	183.4	81.5	126.7	56.9
1988	305.1	115.7	179.1	80.3	121.0	54.2
1989	302.1	114.3	172.8	76.7	113.0	49.0
1990	303.6	116.4	169.9	76.0	107.8	46.4
1991	305.0	118.9	167.0	75.8	102.7	44.2
1992	305.5	120.6	162.8	74.4	96.1	40.6
1993	305.9	122.6	158.5	73.3	89.5	37.2
1994	300.0	118.0	147.5	65.1	75.8	26.6
1995	288.7	107.6	130.4	50.7	55.5	9.3
1996	277.6	97.5	113.2	36.2	35.0	-8.6
1997	268.9	90.8	99.1	25.1	17.8	-22.9

Source: Author's calculation

TABLE 2: Estimated Internal Rate of Return for Canola Yield Increase (1967-1993)

Lag	4 yr.	4 yr.	4 yr.	4 yr.	1 yr.
Depreciation	0%	1%	5%	10%	5%
Year of yield change	Internal Rate of Return				
1971	0.398	0.382	0.324	0.260	0.471
1972	0.384	0.369	0.313	0.252	0.442
1973	0.371	0.356	0.303	0.245	0.425
1974	0.350	0.336	0.285	0.228	0.404
1975	0.336	0.322	0.271	0.215	0.389
1976	0.328	0.313	0.261	0.205	0.375
1977	0.327	0.312	0.261	0.208	0.380
1978	0.318	0.304	0.253	0.201	0.375
1979	0.304	0.289	0.236	0.180	0.355
1980	0.366	0.343	0.262	0.182	0.397
1981	0.353	0.331	0.253	0.174	0.380
1982	0.344	0.323	0.248	0.172	0.369
1983	0.333	0.314	0.243	0.170	0.359
1984	0.319	0.301	0.232	0.159	0.338
1985	0.304	0.286	0.218	0.145	0.315
1986	0.290	0.272	0.208	0.137	0.299
1987	0.276	0.260	0.200	0.134	0.289
1988	0.263	0.248	0.192	0.130	0.275
1989	0.247	0.233	0.181	0.121	0.256
1990	0.235	0.222	0.173	0.118	0.244
1991	0.223	0.211	0.167	0.117	0.231
1992	0.210	0.199	0.159	0.113	0.213
1993	0.198	0.188	0.153	0.112	0.197
1994	0.179	0.170	0.137	0.100	0.171
1995	0.152	0.145	0.114	0.079	0.136
1996	0.126	0.119	0.092	0.060	0.102
1997	0.105	0.099	0.075	0.047	0.076

Source : Calculated from Regression Estimates

4.0 The Returns to Wheat Research - Literature Review

In Canada, quantitative estimation of the return to public investment in crop research and development has been relatively recent. The earliest published evaluation of public investment in wheat R&D we found was performed by Zentner (1982) for the period 1946 - 1979.[4]

In terms of methodology, Zentner used a ten and a seven year lag between the initial investment and the first commercial effect of this expenditure for the wheat breeding and all wheat research and extension respectively. Furthermore, he assumed that the annual future benefits beyond the sample period were equal to the 1977 - 79 average. On the benefit side, he assumed that the aggregate wheat supply curve intersected the price axis at the origin. He also assumed a proportional divergent shift of the supply curve due to technical change. On the cost side, the estimates of the research expenditure were based on information on professional person years (PPY) at different research institutes and estimates of annual average cost of PPY. Finally, Zentner developed the mathematical formulae for the estimation of producer and consumer surplus.

Zentner's results revealed that the average IRR to government investment in wheat breeding research was 34% per year and the marginal IRR 44% per year. He also found the average IRR due to all wheat research and extension programs equaled 39% and the marginal IRR equaled 59%. Two years later, these findings were published in an academic journal as Zentner and Peterson (1984).

In 1985, Ulrich and Furtan (Technical report) updated Zentner's (1982) estimates of IRR in wheat breeding research for the period 1946 - 83. For their model, Ulrich and Furtan adopted the assumption of a ten-year lag between research expenditure and research benefits. Furthermore, they assumed that the annual future returns from 1984 to 2003

were the average of 1981, 1982 and 1983 levels. While the major research costs commenced in 1961 and continued through the period of study, their forecasting methodology assumed that these investment levels would continue through to the year 2003. On the cost side, they adjusted Zentner's estimates of annual professional years on wheat breeding research, and they used the Zentner's (1982) estimates on the annual cost of a professional person year on wheat breeding research. On the benefit side, they assumed that the aggregate wheat supply curve intersected the price axis above the origin and shifted parallel due to technical change. The formulae used to express the producers' and consumers' surpluses were based on the theoretical work of Linder and Jarrett (1978), Rose (1980), and Wise and Fell (1980). Finally, the marginal product of research expenditure in a particular year (proxy for the marginal rate of return) was also estimated econometrically (using regression equation analysis).

The Ulrich and Furtan two-sector model, which included Canada and foreign countries, revealed that the Canadian IRR from higher yielding varieties was 28% per year, and the total IRR from higher yielding varieties was 28%. In dollar terms, they found marginal Canadian benefits of $77.6 for every additional dollar spent on wheat breeding in Canada.

In 1995, Klein, Freeze and Walburger (1995) estimated the rate of return to yield-increasing research on wheat, for the period 1962 - 91. They used a multi-crop mathematical programming model of Canadian agriculture (CRAM) to evaluate the returns from investments in the wheat breeding yield-increasing research. The CRAM model's objective function used the maximization the total surplus (sum of producers and consumers surplus[5]) to find the optimum corresponding production plan, thus allowing substitution between crops. Winter wheat and soft wheat were not included in the analysis. They assumed a ten-year lag between when the research resources were spent to

---

[4] Tosterud et al (1973) estimated the benefit-cost ratio associated with the development of the wheat variety Selking. The found a benefit-cost ratio equal to 79.

[5] Producers' surplus is the total producer revenue less the cost of production. Consumers' surplus is the area beneath the demand curve less the cost of consumption. Yield-increasing technical change shifts the

develop a yield-increasing variety and the adoption of the new variety. They estimated the cost of yield-increasing research for the 1962 - 92 period, and the benefit for the 1972 - 2001 period. On the cost side, they used ICAR's (Inventory of Canadian Agri-Food Research) estimates of the PPY devoted to yield-increasing research on wheat, and the estimates of Agriculture and Agri-Food Canada's Research Branch on cost per PPY. On the benefit side, the differences between consumers' and producers' surpluses for each year and the base year (1991) were used as a measurement of gross benefits from yield-increasing research on wheat. According to Klein, Freeze and Walburger's 1995 study, the IRR from improved research ranged between 27% and 3% at low 1991 prices and from 34% to 38.9% at high 1991 prices. A year later, these estimates were published in an academic journal as Klein, Freeze and Walburger (1996).

Alston, Craig and Pardey (1998) estimated the marginal rate of return to public agriculture research in the United States, while being very careful with the features of the methods used. They developed an econometric model (regression equation analysis) to estimate the returns to agricultural R&D, and to examine the sensitivity of the results to the underling assumptions. On the benefit side, their estimates were based on 48 contiguous states' annual data on agricultural productivity for the period 1848 - 1991. On the cost side, the estimates of the research expenditure on agricultural R&D was based on annual data from the federal and state governments for the period 1890 - 1991. They found the marginal rate of return to public research in the US to be 6.8% per annum, which was much lower than previous reported results. Using the same data, they followed conventional approaches (e.g., short lag; finite lag; truncation of the lags; depreciation of stock of knowledge) to estimate the returns to research, and they found significantly higher rate of returns. They showed that incorrect assumptions with respect to the length and shape/form of the R&D lag relationship, or the lagged adoption of research, can lead to upwardly biased results. In addition, they showed that assumption with respect to the

---

supply curve downward and results in increased in consumers' surplus (as price falls due to increase in production); the effect on producers' surplus is ambiguous.

stock of knowledge has a significant influence on the estimated net returns.[6] They postulated that the empirical evidence of underinvestment, or very high rate of returns, in agriculture research may be due to the incorrect specification of underlying assumptions, which biases the estimated net effect of agricultural research.

Most recently, Alston, Marra, Pardey, and Wyatt (1998) did a meta-analysis to examine the returns to agricultural R&D literature and to examine the sources of differences among studies. Meta-analysis is a systematic analysis of data generated from many previous studies. Alston et al. (1998) collected 294 studies, from the postwar era until today, which provided 1,858 estimates of returns to R&D investment. From this data, they created two subsets of data. In the first one, the highest and the lowest 2.5% of the estimated R&D returns were excluded. In the second one, estimated R&D returns greater than 500% per year were excluded. The first set contained 1,144 observations while the latter set contained 1,181 observations. They found that:

> In the 95 percent data set, the overall average rate of return across all 1,144 observations was 58.6 percent per annum, with a standard deviation of 51.7 (the estimated annual rate of returns averaged 64.2 percent for research only, 46.3 percent for research and extension combined, and 75.6 percent for extension only.) In the second data set the overall average rate of return across all 1,181 observations was 63.4 percent per annum with a standard deviation of 66.7 (the rate of return averaged 70.5 percent for research only, 49.7 percent for research and extension, and 75.6 percent for extension only)(page 27).

Moreover, they used regression equation analysis (regression model) to explore whether, and to what degree, specific features of the methods used affect the estimates of the R&D returns. They found that:

> (1) There is no evidence to support the view that the rate of return has declined over time. (2) The rate of return to research is higher when the research is conducted in more developed countries or when it is adopted in less - developed countries. (3) The rate of

---

[6] For example, if we assume that the depreciation rate is equal to zero, then we impose a restriction that the stock of knowledge never depreciated. On the other hand, if we assume the depreciation rate is equal to one, then we impose a restriction that the stock of knowledge is eliminated in the next period.

return to research varies according to problematic focus, in a way that makes intuitive sense. In general we would expect to see longer production cycles associated with lower rates of return, and the regression results indicate a significantly lower rate of return for natural resource management research (primarily forestry) compared with the other categories. (4) The rate of return is not significantly different between research and extension included individually, but a lower rate of return is found in studies that combine research and extension, which we suspect is a reflection of omitted variable bias in the other studies. (5) Characteristics of the research evaluation itself, and the analyst conducting the evaluation, were found to have important systematic effects on the estimated rates of return, and most of these effects are reasonable.

In short, Alston et al. (1998) found that the characteristics of the analysis affected most previous estimates of R&D returns. Specifically, government analysis' estimates were 33% higher per annum, university analysts' were 28% higher, and international research center analysts' were 22% higher. Moreover, "selfevaluations" yield rates of return estimates were 20% lower per annum than independent studies.

The characteristics of the research evaluation can largely affect the estimates of R&D returns. For instance, while published results in a journal are 10% per annum lower than unpublished ones, R&D results did not change whether experimental yields were used or industry yields. However, the nature of the research-induced supply shift had the biggest effect on the magnitude of R&D benefits estimated. Pivotal supply shifts resulted in smaller returns to research than parallel supply shifts. In addition to the nature of supply shift, the lag length for technological innovation also had a significant effect on the magnitude of estimated R&D benefits. The shorter the lag length used in the analysis, the higher the estimated returns to research. Finally, spillovers, exchange rate distortions, deadweight losses from taxation and the environmental impacts also affected the agricultural rate of returns realized.

As discussed, the characteristics of the rate of return measures affect the estimated benefits from agricultural research investment. Alston et al. (1998) found that the marginal estimates of the returns to research were 10% per annum higher than the

average estimates. Further to the point of this discussion, they found real rate of returns lower than nominal ones.

5.0 Physical Constraints in Wheat Yield Increase in Canada

Wheat (*Triticum aestivum*) is an annual grass of the Gramineae family. In botanical classification, wheats are classified into three broad groups in terms of their chromosome make-up. Diploid wheats have two 7-chromosome sets. Einkorn wheat grown in some west Asian countries is a member of this group. Tetraploid wheats have four 7-chromosome sets (28 chromosomes). The most important member of this group is durum wheat. Hexaploid wheats have six 7-chromosome sets (42 chromosomes) belonging to three genomes (AABBDD). Common or "bread" wheat belongs to this group. *Triticum boeticum* contributed the A genome while the B genome came from *emmer* group of wheat. The D genome in the hexaploids, originated from a wild diploid grass *Aegilops squarrosa* (Williams 1993).

The self-pollinating breeding behavior and the complex hexaploid nature of the wheat genome makes breeding very difficult. Wheat crop production systems in general can be divided into two groups of factors: 1) yield-building factors; and 2) yield-protecting factors. Yield-building factors include genetics, precision planting, and nutrition. Yield-protecting factors are those crop production practices that protect or save yield that has been produced by proper implementation of the yield-building factors (Alley 1990).

Wheat breeding programs in Canada have made improvements in productivity while maintaining grain quality and adequate resistance to numerous disease and insect pests. This progress, which began nearly a century ago, has been the result of basic research that made available unexpected and valuable genetic variation, and which introduced breeding strategies and screening technologies that changed the scope and efficiency of wheat breeding (Campbell and Shebeski 1986). Recent data indicates a decrease in the productivity gains being achieved by major wheat-producing countries. Three overlapping avenues can be considered for raising the yield frontiers in wheat: continued

investments in conventional breeding methods; use of current and expanded genetic diversity; and investigation and implementation of biotechnology-assisted plant breeding (Braun et al. 1998).

Grain yield of wheat is a complex trait influenced by both hereditary and environmental factors. In practice, higher grain yields are usually associated with lower protein concentration that may be detrimental to marketability of the crop, and with delayed maturity that may increase risk of a production failure (due to frost). In Canada the wheat-growing period is severely limited by the climate, which in turn limits the array of cultivars that can be grown. In western Canada the very short frost-free period clearly dictates the use of early maturing cultivars to escape early fall frost and rainy or snowy harvesting conditions. Early maturing cultivars may also escape late summer drought and the devastation of late developing disease epidemics. The greatest disadvantage of early maturity is that it is usually associated with reduced yield potential (Baker 1986).

The inverse relationship between yield and protein content has important consequences on attempts to increase yield potential of wheat cultivars. This limitation due to inverse relationship between grain yield and protein concentration is the probable cause of limited increase in yield potential of Canadian wheat cultivars. When requirements for minimum protein were relaxed, yield increases of approximately 30% over those of bread wheat cultivars were quickly realized (Baker 1986).

The Green Revolution in the Third World countries took place due to development of high-yielding, nitrogen-responsive and lodging-resistant dwarf wheat varieties grown in irrigated conditions. Wheat yields are positively related to moisture availability. To support high plant populations capable of responding to high fertility, a high level of available moisture is necessary. Moisture availability is an important environment constraint for wheat production on the Prairies (Rourke 1986).

Breeding for pest resistance has been one of the most important objectives in the development of new wheat varieties. The interaction between the wheat plant and

damaging pest is a dynamic, constantly changing situation. The breeding of new pest-resistant wheat cultivars will be a never-ending need because as we change the crop management environment, the pest continues to change by mutation or recombination. Introduction of other valuable traits into wheat frequently brings along lower levels of pest resistance (Quick 1990)

It is estimated that about 20% of the wheat harvest is lost each year due to diseases and pests. For several insect pests there is no effective resistance in wheat and so breeding for resistance is not possible through conventional breeding. Wireworms, cutworms, grasshoppers, and wheat midge are in this category (Knott 1986). Biotechnology can give novel sources of resistance for these pests. Although most of the currently recommended cultivars have adequate resistance to stem rust, leaf rust, and root rot, the causal organisms can evolve new, virulent strains that can overcome the resistance of present cultivars. To cope with the continual evolution of new races and to maintain control, plant pathologist and geneticists search for broadly ranging sources of resistance, analyze them genetically, and cooperate with the breeders to incorporate them into suitable cultivars in appropriate combinations, depending on the virulence characteristics of the local pathogen populations. The constantly changing pathogen population always poses a challenge to breeders in developing long-term resistant varieties. Currently, most wheat varieties are susceptible to leaf spots and head diseases of wheat. At the present time there is a drastic need to develop resistant varieties for leaf spots and head diseases of wheat (Saskatchewan Agriculture and Food 1999).

Incorporating large number of resistance genes into a single cultivar, also called gene pyramiding is very difficult using conventional disease breeding, but using marker assisted selection (MAS) gene pyramiding can be easily done. There is presently much emphasis on developing molecular markers linked to resistance genes so that MAS can be practiced in wheat.

Gene transformation is the process of introducing genes into plants by methods that bypass the sexual seed production process. The transformation of canola has been

possible for the last ten years and a number of transgenic varieties have been field-tested and are coming in the market. Wheat currently lies way behind canola, despite transformation technology being demonstrated in wheat. However, a number of impediments exist to the widespread use of this technology. The procedure is still too inefficient, requires too much expertise for routine use, and is limited to only a few varieties or types of wheat. In addition, our general knowledge of transgenic gene expression is insufficient. As a result, most elite breeding lines are not being used for gene transformation. Improvements in the technology are needed to provide efficient and useful wheat transformation, which can be easily employed in applied breeding programs (Barcelo et al. 1998).

The wheat genome is complex due to its hexaploid nature as opposed to the diploid nature of most other cereal crops. The complexity of the wheat genome has delayed the development and application of molecular markers to this species, and wheat lies far behind rice and canola in marker development. The diversity of end-uses and strict quality constraints associated with wheat marketing has resulted in highly narrow germplasm-based breeding programs. The lack of genetic polymorphism in wheat has made it difficult to identify molecular markers (Langridge and Chalmers 1998). No main-line wheat breeding programs routinely use marker assisted selection (MAS) or quantitatively inherited trait loci (QTL). Limitations of MAS or QTL are due to lack of markers for traits of interest, population specificity of a given marker, or their relatively high cost when compared with conventional selection techniques (Braun et al. 1998).

One of the major contributions of tissue culture techniques has been the development of double haploid (DH) systems. Generally, a minimum of two years can be saved in the release of a new cultivar by the development of recombinant DH populations from inter-varietal F_1's. DH systems not only speed up the advance to homozygosity, but can also increase selection efficiency, resulting in speeded development of superior varieties. The DH technology is widely used in canola variety development, but the widespread use of DH technology in wheat has been impeded by lack of: 1) easy, consistent production of large number of DH's of all genotypes in the breeding program; and 2) genetic and

phenotypic stability. In wheat breeding, the DH technology is more expensive than conventional breeding techniques and only a limited number of crosses can be handled. Further research in development of DH technology for wheat breeding is still required (Snape 1996).

Hybrid varieties of any crop usually yield more than normal varieties because of their exceptional vigor (called heterosis), a result of the crosses between two genetically diverse parents. Though successful canola and rice hybrids have been available for years, creating hybrid wheat has proven more difficult and costly. Pickett and Galwy (1997) reported that hybrid wheat production is not economically feasible because of a) limited heterotic advantage; b) higher seed cost; c) lack of advantage in terms of agronomic, quality or disease resistance traits; and most importantly d) heterosis could be fixed in polyploid plants and consequently hybrids would have no advantage over inbred lines.

In Canada, wheat varieties are put into market classes according to the suitability of their flour in manufacturing the various types of food products. Each class is visually distinct, with physical and quality characteristics that must meet standards for that class established by the Canada Grain Act and regulated by the Canadian Grain Commission. Assessment of overall grain quality is based on a number of quality factors including: 1) protein content; 2) milling quality; 3) gluten quality; 4) water absorption; 5) kernel soundness; and 6) end-use product quality.

High protein produces bread with high loaf volume, high water absorption and better storage properties. Wheat with less than 11% protein is unsuitable for bread making unless it is blended with grain of higher protein to raise the overall protein content. Protein content, though influenced by the action of few genes, is highly influenced by environmental conditions (Morris 1998). The goal in milling is to obtain a high yield of good, bright-colored flour. Mineral ash content is an indicator of how well the miller has separated the endosperm from the bran and germ. Wholewheat flour has an ash content of about 1.6% whereas straight-grade flour has 0.5% ash or less. Although hardness of

endosperm is desirable for water absorption, the energy required to mill the grain should not be excessively high (Dexter 1993a).

Gluten quality is related to the ability of flour to produce the desired end product. The most important quality factor in gluten is its strength or ability to stretch and maintain a bubble in dough (Morris 1998). Gluten is a protein and, for the end user, gluten quality and protein content are closely and often inversely related. Kernel soundness is important for consistent bakery products. Soundness refers to the overall visual grain quality. Sound grain is reasonably well matured, non-sprouting and free from kernels damaged by frost, mildew, bleaching, or weather staining (Dexter 1993b).

The vast majority of end-use quality traits may be viewed as polygenic and therefore amenable to genetic analysis that seeks to identify quantitative trait loci. The environment influences all quality traits, some to very high degree. In terms of discrete, well-characterized quality genes in wheat, the number is notably small. Breeding for quality traits without losing grain yield is very difficult (Morris 1998).

The strict quality constraints associated with Canadian wheat marketing have resulted in highly narrow germplasm-based breeding program, which in turn has limited the gains in yield increase. There is an increased need to search for new sources of germplasm for improvement of wheat yield. The growing incentives to protect research discoveries through patents and other forms of intellectual property rights will undoubtedly affect the international flow of germplasm, which is the lifeblood of the breeding programs. Breeding programs may become more insular and less open about sharing breeding lines, because they are fearful of jeopardizing royalty income. Enforcement of intellectual property rights could limit the access to improved varieties and thus reduce wheat productivity. More wheat research resources might be dedicated to cultivar development, because it holds more potential for generating patentable discoveries than other kinds of research, such as pre-breeding. Without adequate levels of investments in pre-breeding, the ability of breeding programs to provide desirable varieties over the long term could decline.

For the public breeder, the number of wheat varieties occupying significant acreage across their breeding territory is an evaluation of how successful they have become. For private breeders', profits resulting in sales of new varieties are what keep them in business. Because wheat is a self-pollinated crop its seed can be used again and again. Lack of sale or illegal sale of protected varieties has been the main factor in preventing private companies from making fair profits in wheat. This has led to a reduction in wheat research in private sector (Sears 1990).

The economics of crop production has also played an important role in low yields of western Canada. Though there are varieties that are higher yielding (but low in protein), farmers are reluctant to grow them because prices tend to be lower. Although a range of wheat classes including Canada Prairie Spring, Canada Utility, and Canada Extra Strong have been available for 20 years, lower yielding Canadian Western Red Spring has remained the choice of most producers. This suggests that the net return to CWRS is higher than for the other wheat classes. Since the Canadian wheat industry is based on exports rather than on domestic needs, it is important that a constant eye be kept on the international wheat trade. Proper projections for demand of low protein and high protein wheat should be made so that farmers can make an informed choice of the wheat class to grow.

6.0 Estimating the returns to research - Description of the Data

The estimation of the returns to wheat research requires an estimate of cost and the benefits of the research over a long period of time. The estimated rates of return will differ depending on the sources of data and the methodology used to estimate the costs and benefits. This chapter outlines the data sources and the methodology used in to estimate the returns to research in this report.

Expenditure

For the purpose of calculating the total research expenditure per year on Canadian Western Red Spring wheat, the total person years invested in the research was multiplied by the total research cost for each year. A total person year (TPY) was used to define both a professional person year and a technical person year. A professional person year (PPY) corresponds to full-time annual work dedicated to professional research (Nagy and Furtan 1977). Similarly, a technical person year corresponds to full-time annual work on technical research (as reported in Inventory of Canadian Agri-Food Research (ICAR)).

The data on total person years devoted to public wheat research activities was estimated from two sources: Zentner (1982) for the years 1946 to 1979, and ICAR (1999) for years 1980 to 1998. Zentner's estimates of PPY covered research activities at the federal government, provincial government and university levels and did not include technical person years. The ICAR estimates of TPY for the overlapping years 1977 to 1979 were 1.57 times greater than the Zentner's PPY estimates. To arrive at an estimate of TPY for the period 1946 to 1979, Zentners's PPY estimates were each multiplied by 1.57.

The ICAR estimates for CWRS wheat included only expenditures for the western provinces (Manitoba, Saskatchewan, Alberta and British Columbia). The ICAR estimates for the TPY dedicated to public CWRS wheat research in Canada, were divided into two periods due to the change of the code that the projects were classified. Prior to 1995, projects could be classified either as wheat in general or as durum, common, and other wheat; from 1996 and onwards, the code became spring, winter, common, and other wheat. After the projects were classified, the number of persons and the percentage of their time devoted in the specific project were estimated, which yielded the projects' TPY. For the purpose of this study, after consulting with ICAR's experts, for the period of 1980 to 1994, the study utilized the category of common wheat for the calculation of PPY. From 1995 to 1998, the study used the sum of the spring wheat category PPY and the general category PPY less the durum projects' PPY recorded in the "general" category. Subtracting the durum projects' PPY included in the general category was necessary because during that period durum projects were booked under both the general and durum category.

Yield Data

The empirical procedure began by converting the relative yield index of different canola varieties to the same variety base (Thatcher) (#1970=100). The yield index for each variety is obtained from the last reported value because it is thought to be a more accurate estimation of the yield performance. The annual yield index was created from an average of the yield index for varieties grown each year, weighted by the seeded acreage. The annual yield in index is shown in Figure 3.

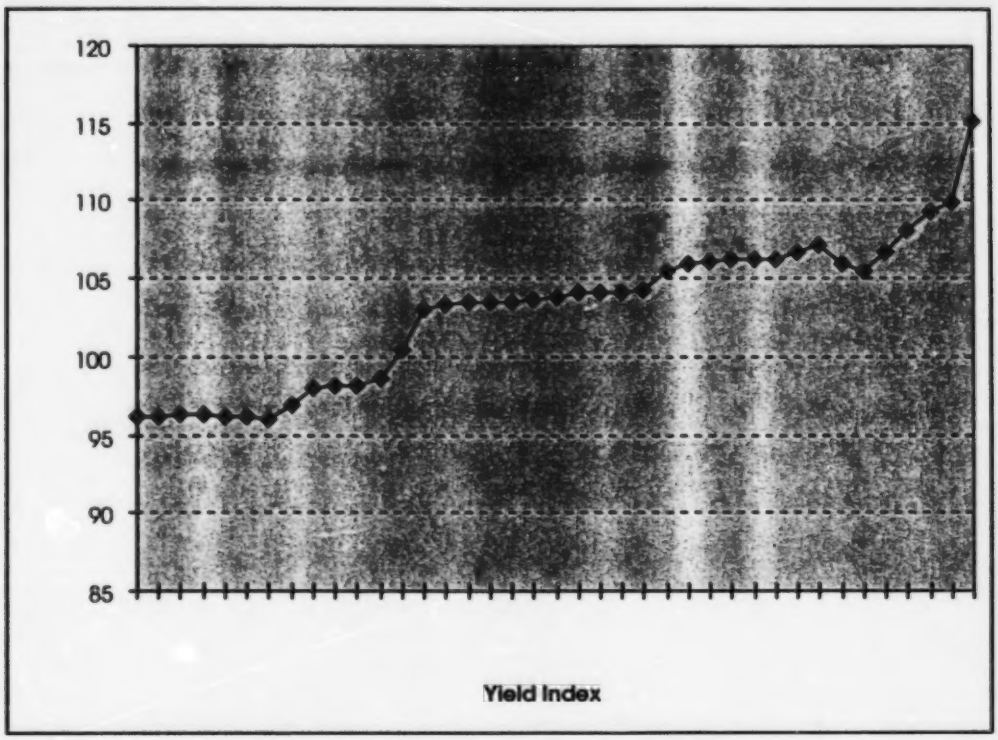

Figure 3: Acreage Weighted Yield Index of Canadian Western Red Spring Wheat

The data on the relative yield of different varieties were obtained from two sources. The first source was Zentner (1982) (from 1960 to 1969). The second source was various issues of Saskatchewan Agriculture and Food, *Varieties of Grain Crops in Saskatchewan*

(from 1970 to 1998). Unfortunately, the whole series was not available from other provinces. Hence, the data from Saskatchewan is used as a national proxy.[7]

The data on the relative yield of different wheat varieties is based on the research station yield trials at a number of locations across Saskatchewan.[8] The wheat varieties were sown and harvested in multiple small plots of 30 feet square to 45 feet square. Agriculture Canada and the University of Saskatchewan conducted the research station yield trials. The yield potential of different wheat varieties is calculated by estimating the weight of grain produced per unit area. The variability of non-genetic factors (e.g., weeds, moisture) is minimized in this estimation of the potential yield. The design of the experiment is such that replication and randomization were used. Hence, the research station yield trials measure varietal performance due mainly to genetic causes.

The data on the percentage acreage of each wheat variety were obtained from three sources. The first source was a 1985 study by Nagy and Furtan, which covered the period 1960 to 1976. The second source was collected from various issues of Prairie Pools Inc., *Prairies Grain Variety Survey* (1977 - 1992). The final source was the authors' estimates based on the Manitoba Crop Insurance Corporation Variety Survey (1993 - 97)[9].

The Adoption Curve

An adoption curve for Canadian Western Red Spring (CWRS) wheat was estimated rather than assuming a specific adoption lag. The weighted average adoption rate of spring wheat varieties was estimated as follows: 1) the individual adoption rate of each CWRS wheat variety was estimated by dividing the acreage sown of each variety by the maximum acreage sown of that variety for each year after the year of introduction. 2) the average adoption rate for each year subsequent to the year of introduction (t to t+n), for

---

[7] It should be reasonably close since Saskatchewan is located in the centre of the canola-growing region.

[8] Research station yield trial data was used in this estimation. Actual yield data was not used because it would be extremely difficult to isolate the genetic affects on actual yields from the non-genetic factors such as weather, soil type, weeds, diseases, and nutrients.

[9] The prairie variety survey was ended in 1992. The proportion of acres grown in Manitoba was used to create the weighted average post 1992.

all varieties, was calculated. The average adoption curve for CWRS is reported in Figure 4.

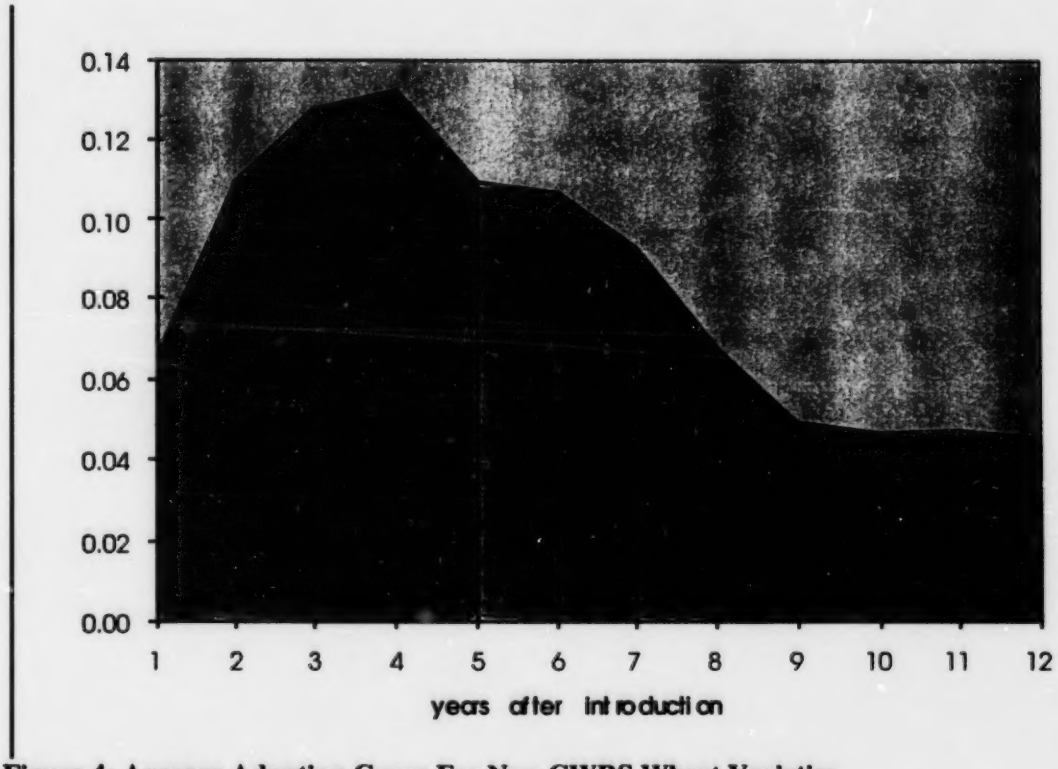

Figure 4: Average Adoption Curve For New CWRS Wheat Varieties

That weighted average adoption rate of spring wheat varieties was applied to the cost data to create a variable of the weighted lag research expenditure. The adoption curve means that on average the acreage planted to varieties is a function of the year varieties are introduced. The annual weighted yield index is an average of the yield of varieties previously introduced weighted by the respective coefficients on the adoption curve. Mathematically,

$$Y_t = \sum_{i=1}^{n} \gamma_i y_{t-i} \qquad (4)$$

where Y_t is the yield index in year t , γi is the weights on the adoption curve, and y_{t-i} is the average reported yields of the varieties introduced in year t –i. Given this relationship it follows that the annual change in the weighted yield index is a weighted average of the changes in the yield of the varieties introduced, or:

$$dY_t = \sum_{i=1}^{n} \gamma_i dy_{t-i} \qquad (5)$$

where *dY* and *dy* represent the change in the weighted index and the yield of new varieties. If change in new variety yield is proportional to the lagged expenditures on research or

$dy_t = \rho X_{t-g}$, where X_{t-g} is the expenditures in year t – g, and g is the gestation lag, then

$$dY_t = \rho \sum_{i=1}^{n} \gamma_i X_{t-i-g} \qquad (6)$$

Making these assumptions, the change in the annual weighted yield index is proportional to the adoption curve weighted with previous yield expenditures.

Price of Wheat, CPI, Quantity

The data on the farm price of spring wheat in Canada were obtained from two sources. The first source was Saskatchewan Agriculture and Food, *Agricultural Statistics 1997.* The second source was the authors' estimates based on the Canadian Wheat Board, *Pool Return Outlook* and Canadian Wheat Board, *News Release.* The farm price of wheat in Saskatchewan was used because it is by far the largest producer of wheat. The price of The data for the consumer price index (CPI) was obtained from Statistics Canada, *Direct Cansim Time Series: CPI and All Goods for Canada, (1999).* The CPI was converted to the same base year (1998). Finally, the quantity of wheat production was obtained from Statistics Canada, *Direct Cansim Time Series: Spring Wheat /Production, Metric Tonnes, Spring Wheat – Canada, (1998).*

7.0 Econometric Analysis

Econometrics as a tool to estimate a statistical relationship between research expenditures and subsequent changes in yield. Such a relationship could be used to accurately estimate both the marginal and average rate of return to research. Econometric procedures require a significant amount of data to provide reliable estimates. If the data is made up of time series then tests must be performed to guard against estimating spurious relationships.. This chapter outlines the procedures used and the results of the econometric analysis.

Before the effect of a research expenditure on the level of wheat output (here the wheat output generated from research expenditure is measured by the change in the yield in one period[10]) could be estimated, the time-series properties of the variables in the model had to be examined. Specifically, to avoid estimating a spurious relationship between wheat output and expenditure, due to a unit root problem, individual series were tested for the presence of a unit root (i.e., I(1)). By definition, the variable y (denoted as I(0)) is said to be I(1) or integrated of order 1 if the first difference of the series is stationary.

The test statistic used in this report is the Augmented Dickey-Fuller (ADF) test of the form:

(1) $$\Delta y_t = \mu + \theta t + \delta y_{t-1} + \sum_{j=1}^{l} \beta_j \Delta y_{t-j} + \varepsilon_t$$

where Δ represents the change in the variable. The null hypothesis under test is H_0: $\delta = 0$ (or the variable y is I(1)). If the null hypothesis is rejected, then the variable is an I(0) series and hence stationary. If the null hypothesis is not rejected, then the variable is at least an I(1) series. In this case, the variable is differenced and the ADF is performed again.

From (1), in order to implement the ADF test, the appropriate lag lengths of each variable under test need to be determined. This is done by first running regressions in (1) for

---

[10] The expenditure on wheat R&D generates change in yield index. Hence, the change in yield index is a measurement of the output of wheat research. For simplicity, in that part of the analysis, we will use the terminology level of wheat output instead of change in yield index.

various lag lengths (l). The lag length is then determined by the regression that minimizes the Akaike Information Criterion (AIC).

The ADF test revealed that, for the research expenditure series, the ADF statistic is –2.491 with the 5% critical value of –2.956. Thus, the unit root hypothesis could not be rejected in favor of stationary. However, when the research expenditure is measured in the first difference, the unit root hypothesis is rejected in favor of stationary, with the ADF statistic of –3.476. For the output level, the ADF test also indicated that the series are not stationary. The ADF statistic for this case is –1.983 with the 5% critical value of –2.956. However, when taking the first difference, the unit root hypothesis is rejected in favor of stationary with the ADF statistic of –4.634. Note that the appropriate lag determined by the AIC in all cases above was one.

Given the above finding about the nature of the two series, the relationship between the wheat output and the research expenditure can be modeled in three ways.

The first approach is to ignore the possible existence of unit roots in the series and run a classic regression hoping that the unit roots do not exist. When this was done a coefficient was estimated that indicated an increase of 1% in adoption weighted 5-year lagged research expenditure resulting in .036% increase in the yield index. Unfortunately, there is little reliability in this estimate because a unit root in either the dependent or independent variable could result in a spurious estimate. This approach was rejected and the estimated coefficient is used only for comparison purposes with other methods.

The second econometric approach is to take the first difference on each of the series so that both series are now stationary and hence a classical regression can be preformed relating the wheat output and research expenditure and/or its lags. However, this approach is not intuitively appealing. For instance, using a first difference in expenditure, yield change would be a function of the rate of change of expenditure rather than the level of expenditure.

A third econometric approach, which is more intuitively appealing, is to use the cointegration analysis introduced by Engle and Granger (1987). The basic idea behind cointegration analysis is that if a set of variables are integrated of the same order (i.e., I(1)), it is quite possible for there to be a linear combination of these integrated variables that is stationary. The concept of cointegration relates to, or in a sense mimics, the concept of long-run equilibrium. To see this, suppose a long-run equilibrium relationship was defined by $y_t = \alpha + \beta x_t$ or $y_t - \alpha - \beta x_t = 0$. In this case, $e_t = y_t - \alpha - \beta x_t = 0$ would represent how far y_t and x_t were away from equilibrium (and it could be called "equilibrium error"). If y_t and x_t are cointegrated and the error e_t is stationary with mean 0, then $y_t = \alpha + \beta x_t + e_t$. Since e_t is stationary, the variables y_t and x_t obey a stable, long-run relationship. Thus, the equilibrium relationship among a set of non-stationary variables means that the variables cannot move independently from each other. Note that the coefficient β is called "cointegating vector", and can be regarded as the long-run response of a change in y to the change in x.

Given that the level of output and level of research expenditure are both I(1), and to investigate any possible long-run relationship between them, the second approach was adopted for the analysis in this report.

First, before any long-run relationship between the level of output and the level of research expenditure can be examined, cointegration between the two series needs to be determined. The Likelihood Ratio (LR) test for cointegration proposed by Johansen (1988) can do this. The null hypothesis is that there is no cointegrating vector against the alternative of at least one cointegrating vector. If the test fails to reject the null hypothesis, then cointegration does not exist in the model. If the null hypothesis is rejected, then there exists at least one cointegrating vector. For a more detailed description of Johansen's LR test for cointegration, see for example Greene (1997).

The LR test was found to be 18.338 with the lag length of 1 (lag length was determined by AIC) and the null hypothesis of no cointegrating vector is rejected at the 5% significance level (5% critical value is 15.41). Thus, there exists at least one cointegrating

vector, indicating that there is a long-run co-movement between the level of output and the level of research expenditure. The cointegrating coefficient was found to be 0.8044, which is significant at the 5% level, revealing that a 1% increase in research expenditure will lead to a 0.8044% increase in the level of output (% change in the yield index) in the long run.

Next, a test for Granger causality between the level of output and the level of research expenditure was conducted to examine whether there is any casual flow among the two series. That is, to test whether the past values of research expenditure help in explaining the movement in the level of output or vice versa. The following regressions were run:

(2) $$\Delta OUTPUT_t = \alpha_1 + \sum\beta_{1j}\Delta OUTPUT_{t-j} + \sum\delta_{1j}\Delta R_{t-j} + \varepsilon_{1t}$$

(3) $$\Delta R_t = \alpha_2 + \sum\beta_{2j}\Delta OUTPUT_{t-j} + \sum\delta_{2j}\Delta R_{t-j} + \varepsilon_{2t}$$

where R is research expenditure

For regression (a), testing the null hypothesis that research expenditure does not Granger cause output is equivalent to testing the set of coefficients $\delta_{1j} = 0$, for all $j = 1,2,3,p$, where p is the number of lags included in the regression using the conventional F-test statistic. The maximum lag length used in the regression was 10 and those lags that are not significant were dropped from the regression. The maximum F-statistic for this regression is 4.303 (with $p = 5$) which exceeds the 5% critical value of 2.55. Therefore, the null hypothesis is rejected, indicating that there exists a positive casual flow from research expenditure to output level in the sense that an increase in research expenditure will lead to a higher output level. Intuitively, the result seems reasonable since it will take approximately 5 years from the initial research funding to change yield.

For regression (b), the null hypothesis of $\beta_{1j} = 0$ for all $j = 1,2,3,p$, cannot be rejected at the 5% level of significance with the F-statistic of 1.649 (with $p = 5$) and, hence, there exists no casual flow from output to research expenditure.

Overall, the econometric results linking research expenditures to yield increases provided some evidence of a long term relationship but failed to reveal a short term estimate. Unit

roots could not be rejected in either research expenditure or in yield change, making classical regression results unreliable. The co-integration estimates did provide some evidence that some long-term relationship between the expenditure and change in yield and further Granger causation analysis suggested that expenditures tended to lead changes in yield.

The failure to come up with a short term estimate is not surprising when the nature of the data as presented in Figure 3 is considered. Despite relatively constant research expenditures, yield increases have historically been restricted to a few relatively short periods after a new exceptional variety was introduced. Obviously, without research expenditures these exceptional varieties would not be created. However, the existence of expenditures is unlikely to increase yield in a particular year. The research process is more like mineral exploration than a simple production process where input begets output. Thus, the sporatic relationship is likely to defy econometric estimation of a constant relationship between expenditure and change of yield.

8.0 The Returns to Wheat Research

Despite the failure to estimate a short run econometric relationship it is possible to estimate the average rate of return to expenditures on wheat research. Any increase in the genetic yield of new varieties is some product of genetic research. An average rate of rate return can be estimated by calculating the overall benefits of the yield increase, and comparing this to the lagged expenditure in research.

For the purposes of this report the returns for wheat research are calculated from a total or Canadian perspective. The increase in wheat yield was assumed to provide additional revenue to the producer at no additional cost. This increase in revenue was applied to the actual farm value of wheat grown historically. This methodology implicitly assumes that the profits beyond the farm gate are not affected by wheat yield increases and that the

prevailing prices would were not influenced by the changes in yield.[11] For the projections into the future, the conservative 1998 revenue was assumed to remain constant in real terms indefinitely into the future.

Following Alston et al. (1997) the increase in yield in a specific year was assumed to contribute to the genetic stock for yield. That is, once a variety is introduced, other varieties can build on these advances to increase yield further. Over time the contribution of this advance would depreciate due to the adaptation of pests to these new genetic lines. For the purposes of calculation we examined several depreciation rates: .5%. 1% and 5% per year.

The lagged expenditure attributed to the increase in the yield index in a particular year was calculated in two ways for the sake of comparison. The first method was to use the adoption curve to weight previous expenditures as outlined above in Section 6. In this method the lag between expenditure and the yield increase represents the gestation period between the expenditure and the first year of adoption. The effective lag in this case is the gestation lag plus the average lag in the adoption curve of 5 years. For instance, a lag of 4 years is effectively a lag of 4 plus 5 or 9 years. The second method was to attribute the change in year to a particular year of research expenditure. Here the lag represents a point estimate of the gestation lag and the adoption lag. Here a lag of 8 years indicates a lag of eight years between the year of expenditure and the maximum impact of that impact on yield index.

The annual present value of costs and the net present value of new wheat varieties calculated at an 8% real discount rate are shown in Figure 5 below. There are two points evident from the figure. The net present value is sporatic with some very large positive values, the innovations in wheat being far less frequent than in canola but very significant when they are made. The peaks represent the adoption of Neepawa, Katepwa and AC

---

[11] For the period in question CWRS wheat made up about 5% of total world wheat production. Even a 20% increase in CWRS wheat yield would increase world supplies by approximately 1%. Given the large long run elasticities of supply, CWRS yield increases would have a very small impact on price.

Barrie wheat. The peak adoption of these varieties had a net present value of $1 billion, $2 billion and $1.9 billion respectively. The negative values represent the adoption of solid stem sawfly resistant wheat, which has a lower test plot yield but may perform better that previous varieties in field conditions.

The large net present value of benefits is in contrast to the research expenditures, which have a present value of $80 million per year. As shown in Table 3, even using a relatively high 8% real discount rate, the present value of benefits exceeds the present value of costs by a four to one ratio. This suggests that expenditure on yield increasing wheat research has a high internal rate of return. The high internal rates of return (IRR) are evident in Table 4. In this table the IRR are calculated with the adoption curve weight expenditure lag structure and the unweighted structure using both a 1% and 5% rate of yield depreciation. The real IRR vary from a low of 17% per year to a high of 36% per year depending upon the lag and depreciation assumptions. Even the lowest IRR make wheat research a very attractive investment from a social perspective.

The IRR reported in Table 5 are broken down by decade. Here, despite the sporatic returns, the IRR in each decade have been well above market rates. There is little evidence that the rates of return are decreasing. The lowest rates occurred during the 1980's and increased again during the 1990's with the introduction of AC Barrie wheat.

Table 3: Present Value of Yield Increasing Benefits and Costs of Research for CWRS Wheat 1960-1997

Year of Index Change	Present Value Benefits	Present Value Costs	Net Present Value
		Million 1998 $	
1961	46	60	-14
1962	46	60	-14
1963	0	61	-61
1964	-33	63	-96
1965	-121	62	-182
1966	-54	64	-118
1967	925	64	861
1968	1103	65	1038
1969	204	65	140
1970	-20	66	-86
1971	450	68	382
1972	1809	67	1741
1973	2695	70	2625
1974	318	72	245
1975	75	73	1
1976	82	74	8
1977	9	77	-68
1978	137	75	62
1979	90	74	16
1980	174	74	100
1981	90	73	17
1982	-49	72	-121
1983	134	73	61
1984	707	74	633
1985	317	78	239
1986	113	80	33
1987	52	79	-27
1988	29	80	-51
1989	-6	82	-88
1990	228	79	149
1991	256	76	180
1992	-648	77	-725
1993	-263	77	-340
1994	676	77	598
1995	683	85	598
1996	636	81	555
1997	303	83	221
1998	2481	71	2411
Average	360	72	287

Source: As Calculated with weighted expenditures, a four year gestation lag and a 8% real discount rate

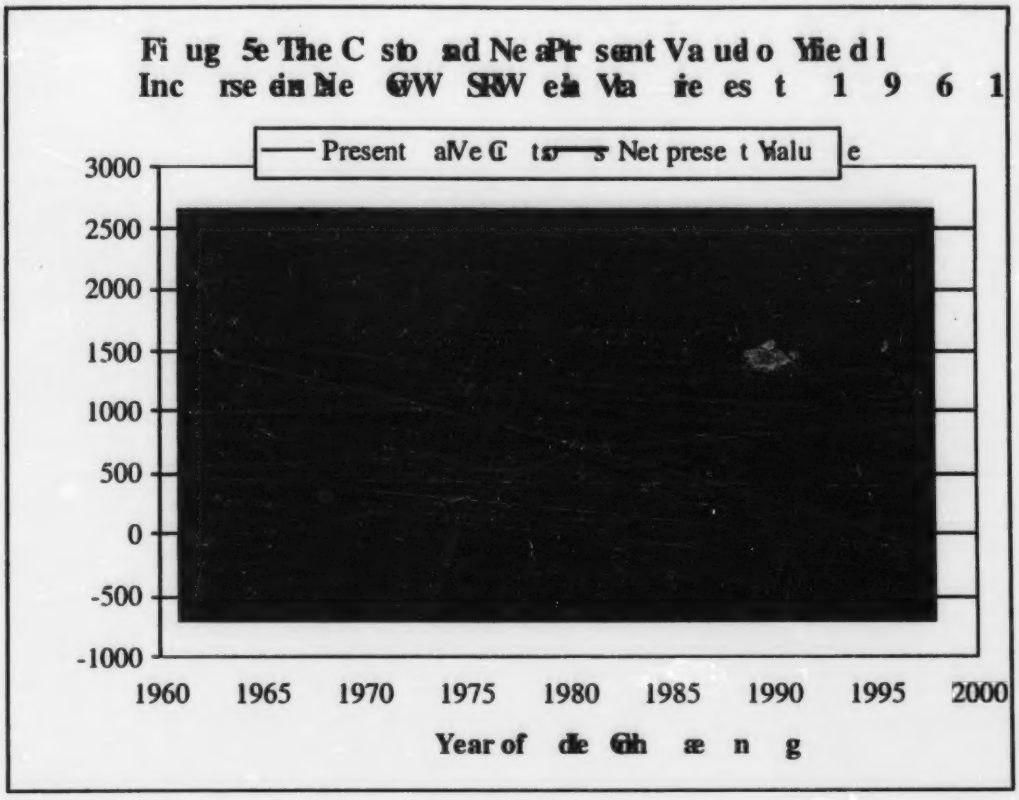
Present aIVe Ct ts Net prese t Valu e
3000
2500
2000
1500
1000
500
0
-500
-1000
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year of

Table 4: Average IRR for *Yield Increases in CWRS Wheat in Western* Canada 1960-1997 Calculated with Fixed Gestation Periods

	Weighted Cost*	Unweighted Cost
	Yield Depreciation = 1%/yr.	
Lag=2	0.21	-
Lag=4	0.21	-
Lag=6	0.21	0.36
Lag=8	0.22	0.30
Lag=10	-	0.26
Lag=12	-	0.23
	Yield Depreciation = 5%/yr.	
Lag=2	0.17	-
Lag=4	0.18	-
Lag=6	0.18	0.31
Lag=8	0.18	0.26
Lag=10	-	0.23
Lag=12	-	0.20

*Weighted Cost is weighted by the average adoption curve
Source: As calculated by authors from expenditure and yield index data

Although these rates of return are large they may be an underestimate of the true values. In the analysis presented so far there has been no allowance made for the wheat variety research that is directed toward disease resistance. New varieties are typically bred to be resistant to the most prevalent forms of leaf rust, stem rust and root rot. Thus, some innovation is required just to maintain yield and one of the benefits of research is yield maintenance. In Table 6 the IRR are recalculated assuming that the new varieties have served to maintain existing yields. As shown in the table, even a modest maintenance function dramatically increases the IRR to research. This suggests that this role may be an important, but often overlooked, benefit excluded from many rate of return studies.

Table 5: Average IRR for CWRS wheat in Western Canada selected periods calculated with fixed gestation periods

	Lag=2	Lag=4	Lag=6	Lag=8	Lag=10	Lag=12
			Weighted Cost			
			Delta=0.01			
1960-69	0.17	0.17	0.17	0.18	-	-
1970-79	0.33	0.33	0.33	0.33	-	-
1980-89	0.16	0.16	0.16	0.16	-	-
1990-97	0.21	0.21	0.21	0.21	-	-
			Delta=0.05			
1960-69	0.13	0.13	0.14	0.14	-	-
1970-79	0.28	0.29	0.29	0.29	-	-
1980-89	0.12	0.12	0.12	0.12	-	-
1990-97	0.17	0.17	0.17	0.17	-	-
			Unweighted Cost			
			Delta=0.01			
1960-69	-	-	0.32	0.26	0.22	0.19
1970-79	-	-	0.68	0.52	0.42	0.34
1980-89	-	-	0.38	0.29	0.23	0.19
1990-97	-	-	0.39	0.32	0.26	0.23
			Delta=0.05			
1960-69	-	-	0.26	0.21	0.18	0.16
1970-79	-	-	0.60	0.46	0.37	0.31
1980-89	-	-	0.30	0.23	0.19	0.15
1990-97	-	-	0.33	0.27	0.22	0.19

Source: Authors calculations

Table 6: Average IRR for CWRS wheat in Western Canada selected periods calculated with fixed gestation periods when research maintenance is considered

	Annual % Yield Maintenance from Variety Research		
	.1%	.5%	1%
	Internal Rate of Return		
	Delta=0.01		
Lag=2	0.24	0.33	0.40
Lag=4	0.25	0.34	0.40
Lag=6	0.25	0.34	0.41
Lag=8	0.25	0.35	0.42
	Delta=0.05		
Lag=2	0.20	0.29	0.35
Lag=4	0.21	0.29	0.35
Lag=6	0.21	0.30	0.36
Lag=8	0.22	0.30	0.37

Source: As calculated by authors from expenditure and yield index data

In an attempt to measure the effectiveness of marginal expenditure the econometric approach was pursued as part of this study. The estimate of direct relationship between lagged expenditure and the change in yield was not possible given the possibility of a unit root and the resulting possibility of a spurious relationship. An examination of Figure 5 gives some indication of the econometric problem. The increases in yield were quite sporadic despite a continuous research effort, indicating a weak short term relationship. The econometric analysis did find that yield and research expenditure were co-integrated meaning that a long term relationship between these variables did exist. The test of Granger causality also showed that the change in yield was a function of past research expenditures.

The returns to research based on the coefficient in the classical regression is reported in Table 7. Using weighted costs the estimates were slightly higher than those directly calculated from yield and expenditure data.

Overall, the various approaches calculated the real internal rate of return at 17 - 36%, and even higher rates when disease resistance is considered. The benefits to yield-increasing wheat research is very sporatic in nature. The discovery of Grandon wheat has a value exceeding $2 billion with very limited benefits created in the previous decade.

As with previous studies, these rates of return are well above market returns of 3 - 10%. Furthermore, there is no evidence that these rates of return have decreased.

Table 7: IRR for CWRS wheat in Western Canada selected periods calculated using regression results*

	Weighted Cost
	Delta=0.01
1960-69	0.30
1970-79	0.29
1980-89	0.24
1990-97	0.21
Average	0.30
	Delta=0.05
1960-69	0.25
1970-79	0.25
1980-89	0.21
1990-97	0.17
Average	0.25

Source: As calculated from regression coefficients by authors

*The unit root could not be rejected in either the change in yield and the level of expenditure. Thus there is a reasonable possibility that these results are spurious. They are reported only for the sake of comparison to the non-econometric results.

9.0 Policy lessons

This paper examines the nature of the return to wheat research. In doing so it addresses the question of whether the lack of private research in wheat reflects low expected social returns or the lack of effective intellectual property rights.

The rate of return analysis showed that the benefits of yield-increasing CWRS wheat research were captured largely in a few "breakthrough" varieties that produced significant yield increases. Despite the sporatic nature of the research result, the social internal rate of return for yield-increasing wheat research has been much above the market rates of return, with no signs of diminishing.

The rates of return to yield-increasing wheat research are very different than Gray et al. (1999) found for canola research, where the yield increases have been relatively steady and the rates of return have been toward market rates with the large influx of research investment. Canola is known as the Cinderella crop and has attracted a great deal of private and government research support while wheat has been one of her ordinary stepsisters. Canola has attracted so much of the public and private investment that wheat is a far better social research investment.

These rates of return for canola and wheat research are consistent with the simple economic theory presented in Section 2.0. There may be overinvestment occurring in canola research because the intellectual property rights are nearly complete and the government offers Matching Investment Initiatives. In wheat, however, breakthrough varieties are released every decade or more, and farmers retain and multiply wheat seed for their own use. This gives little opportunity for the breeders to capture a significant portion of the value created by a breakthrough variety. Moreover, breakthrough varieties in wheat are very rare and have occurred many years apart, despite a continual research program. This makes research for new varieties of wheat a very risky investment for scientists, for government stations and especially for private firms.

The lack of private sector involvement and the continuing high rate of return to wheat research suggests that research may be among the most cost-effective instruments to mitigate the long term decline in grain incomes. The analysis here suggests that even with an 8% real discount rate, investments in wheat research have had a four-to-one payoff in returns, with much of the payoff going to producers.

These high returns to wheat research are in part due to the large area seeded to wheat each year. A 1% increase in revenue from a $2 billion crop produces a stream of benefits of $20 million per year. Even with combined depreciation and a real discount rate of 10% this additional stream of income has a present value of $200 million dollars. In contrast, a research program for a crop with $100 million in sales would have to achieve a 20% increase in yield to have the same economic impact as a 1% increase for wheat. Thus the existing or potential scale of the crop has to be an important consideration in research choice.

This study also showed that maintenance of disease resistance is an economically important function of wheat research. Even modest amounts of yield maintenance significantly increase the rate of return. More work should be done to quantify these effects.

The willingness of private firms to invest is not a good indicator of whether government should support research. In fact the opposite can be the case. In canola, a flood of private research dollars has reduced the return to research. This suggests that the existence of property rights should temper government involvement in applied research programs. In the case of canola, it is clear that many years of basic public research allowed the industry to develop. However, once the industry had developed and property rights were established, this diminished the role for government.

In the wheat sector, foreign government subsidies, changes in domestic transport costs, and the Green Revolution driven by semi-dwarf varieties have challenged the wheat sector and have shifted the comparative advantage away from the cold and arid regions of

western Canada. Incomes in western Canada have been in a long period of decline and the dominance of wheat has diminished. Some might conclude that this indicates a need to move research dollars away from wheat toward other crops. However, the large returns to wheat research calculated in this study show something very different. Wheat is still a very large crop and the returns to research are high. Any increases in yield on this large production base create tangible benefits for producers.

Finally, effective property rights can change the distribution of the returns to research. Plant Breeders Rights do not allow the effective capture of the returns for wheat breeders. Rather, wheat producers are able to retain much of the benefit of the research with a one-time purchase of seed that is used for the seed for subsequent crops. With the potential introduction of herbicide-tolerant varieties this distribution could change dramatically. With these varieties, the right to grow is renewed on an annual basis through the use of technology use contracts, which allow the breeders to capture nearly the full economic benefit of the innovation. The capture of these benefits is a transfer from producers to breeders. As long as governments make expenditures to support agricultural incomes there will be indirect fiscal consequences of research policy that need to be carefully considered in the design of research policy.

Literature Cited

Akgüngör, S., D.W. Makanda, J.F. Oehmke, R.J. Myers, and **Y.C. Choe.** 1996 "Dynamic Analysis of Kenyan Wheat Research and Rate of Return." Contributed paper, proceedings from the Conference on *Global Agricultural Policy for the Twenty-First Century*. Melbourne, Australia. August 26-28. p. 333-366.

Akino, M. and U. Hayami. 1975 "Efficiency and Equity in Public Research: Rice Breading in Japan's Economic Development." *American Journal of Agricultural Economics.* 57: 1-10.

Alley, M. M. 1986. "Managing for High Yields: a Research Perspective." *In* Reynolds, M. P., Rajaram, S., and McNab, A. (eds.) *Increasing Yield Potential in Wheat: Breaking the Barriers*. Proceedings. Workshop. March 1996. Ciudad Obregon, Sonora, Mexico.

Baker, R.J. 1986. "Breeding Wheat for Yield." P. 443-452. *In* Slinkard, A. E. and Fowler, D. B. (eds) *Wheat production in Canada-A Review. Proceedings of the Canadian Wheat Production Conference.* 3-5 March, 1986. Saskatoon, Canada.

Alston, J.M. and H.O. Carter. 1994. *Valuing California's Agricultural Research and Extension*. Davis: University of California Agricultural Issues Center Publication No. VR-1, March.

Alston, J.M., B.J. Craig, and **P.G. Pardey. 1998** . *Dynamics in the Creation and Depreciation of Knowledge, and the Returns to Research.* GPTD Discussion Paper. No.35 (August). Washington D.C.: International Food Policy Research Institute.

Alston, J.M., G.W. Norton, and **P.G. Pardey. 1997.** *Science Under Scarcity: Principles and Practice for Agricultural Research Evaluation and Priority Setting.* Ithaca and London: Cornell University Press.

Ayer, H.W. and **G.E. Schuh. 1972.** "Social Rates of Returns and Other Aspects of Agricultural Research: The Case of Cotton Research in Sao Paulo, Brazil." *American Journal of Agricultural Economics* 54: 557-569.

Barcelo, P., Rasco-Gaunt, S., Sparks, C., Cannell, M., Salgueiro, S., Rooke, L., He, G. Y., Lamacchia, C., De La Vina, G., Shewry, P. R., and Lazzeri, P. A. 1998. "Transformation of Wheat: State of the Technology and Examples of Application." *In* Slinkard, A. E. (ed) *Proceedings of the 9th International Wheat Genetics Symposium.* 2-7 August, 1998. Saskatoon, Canada

Braun, H. J., Payne, T. S., Morgounov, A. I., van Ginkel, M., Rajaram, S. 1998. "The Challenge: One Billion Tons of Wheat by 2020." *In* Slinkard, A. E. (ed) *Proceedings of the 9th International Wheat Genetics Symposium.* 2-7 August, 1998. Saskatoon, Canada

Campbell, A. B. and Shebeski, L. 1986. "Wheat in Canada- Past and Present." p1-14. *In* Slinkard, A. E. and Fowler, D. B. (eds) *Wheat production in Canada-A Review.* Proceedings of the Canadian Wheat Production Conference. 3-5 March, 1986. Saskatoon, Canada.

Canadian Food Inspection Agency. 1998. *Canadian Varieties. January 1, 1923 to June 24, 1998.* Special Tabulation from the Plant Health and Production Division.

Canola Council of Canada. 1998. *Canola Growers' Manual.* http://www.canola-council.org/manual/canolafr.htm.

Canola Research Survey. 1997. College of Agriculture. University of Saskatchewan.

Chavas, J.-P. and **T.L Cox. 1992.** "A Nonparametric Analysis of the Effects of Research on Agricultural Productivity." *American Journal of Agricultural Economics* 74: 583-591.

Davis, J.S. 1980. "A Note on the Use of Alternative Lag Structures for Research Expenditure in Aggregate Production Function Models." *Canadian Journal of Agricultural Economics* 28: 72-76.

Dexter, J. E. 1993a. "Quality Requirements of Western Canadian Bread Wheats." p. 697-722. *Grains & Oilseeds: Handling, Marketing, Processing*. Canadian International Grains Institute. Winnipeg, Manitoba, Canada.

Dexter, J. E. 1993b. "End-use quality implications of grading factors in wheat." p. 739-778. *Grains & Oilseeds: Handling, Marketing, Processing*. Canadian International Grains Institute. Winnipeg, Manitoba, Canada.

Downey, K. 1995. Personal Communication. 1995.

Evenson, R.E. 1967. "The Contribution of Agricultural Research to Production." *Journal of Farm Economics* 49: 1415-1425.

Evenson, R.E. 1996. "Two Blades of Grass: Research for U.S. Agriculture." Chapter 11 in J.M. Antle and D.A. Sumner (eds.) *The Economics of Agriculture Volume 2, Papers in Honor of D. Gale Johnson.* Chicago: University of Chicago Press. p.171-203.

Forhan, M. 1993. "Canola Breeding Goes Private." *Canola Guide.* p. 28-31.

Griliches, Z. 1958. "Research Costs and Social Returns: Hybrid Corn and Related Innovations." *Journal of Political Economy* 66: 419-31.

Huffman, W.E. and **R.E. Evenson. 1992.** "Contributions of Public and Private Science and Technology to U.S. Agricultural Productivity." *American Journal of Agricultural Economics* 74(August 1992): 752-756.

Huffman, W.E. and **R.E. Evenson. 1989.** "Supply and Demand Functions for Multiproduct U.S. Cash Grain Farms: Biases Caused by Research and Other Policies." *American Journal of Agricultural Economics* 71: 761-773.

Huffman, W.E. and **R.E. Evenson. 1993.** *Science for Agriculture: A Long-Term Perspective.* Ames: Iowa State University Press.

ICAR (Inventory of Canadian Agri-Food Research) 1998. Special Tabulation Upon Request. 1998.

ISI (Institute for Scientific Investigation). 1997. Citations Database, Special Tabulation of Academic Publications Based on Key Word Search for Canola. November, 1997.

Langridge, P. and Chalmers, K. 1998. "Techniques for marker development." p. 107-117. *In* Slinkard, A. E. (ed) *Proceedings of the 9th International Wheat Genetics Symposium*. 2-7 August, 1998. Saskatoon, Canada

Leiby, J.D. and **G.D. Adams. 1991.** "The Returns to Agricultural Research in Maine: The Case of a Small Northeastern Experiment Station." *Northeastern Journal of Agricultural and Resource Economics* 20: 1-14.

Makki, S.S., L.G. Tweeten, and **C.S. Thraeu. 1996.** "Returns to Agricultural Research: Are we Assessing Right?" Contributed paper, proceedings from the Conference on *Global Agricultural Science Policy for the Twenty-First Century*. Melbourne, Australia, August 26-28, p. 89-114.

Malla, S. 1996. *The Distribution of the Economic and Health Benefits from Canola Research.* M.Sc.Thesis, University of Saskatchewan.

Malla, S., R. Gray, and P.W.B. Phillips. 1998. *The Evolution of Canola Research: An Example of Success*. Saskatchewan Agriculture and Food.

Manitoba Crop Insurance Corporation. 1993-97 *Variety Summary.*

Morris, C. F. 1998. "Genetic determinants of wheat grain quality." p. 245-253. *In* Slinkard, A. E. (ed) *Proceedings of the 9th International Wheat Genetics Symposium*. 2-7 August, 1998. Saskatoon, Canada

Myers, R.J. and **T. Jayne. 1996.** "Regime Shifts and Technology Diffusion in Crop Yield Growth Paths: An Application to Maize Yields in Zimbabwe." Contributed paper, proceedings from the Conference on *Global Agricultural Science Policy for the Twenty-First Century.* Melbourne, Australia. August 26-28, 1996. p.63-88.

Nagy, J.G. and **W.H. Furtan. 1978.** "Economic Costs and Returns from Crop Development Research: The Case of Rapeseed Breeding in Canada." *Canadian Journal of Agricultural Economics* 26: 1-14.

Nagy, J.G. and **W.H. Furtan. 1997.** *The Socio-Economic Costs and Returns from Rapeseed Breeding in Canada.* Department of Agricultural Economics. Saskatoon: University of Saskatchewan.

Pardey, P.G. and **B. Craig. 1989.** "Causal Relationships Between Public Sector Agricultural Research Expenditures and Output." *American Journal of Agricultural Economics* 71: 9-19.

Peterson, W.L. 1967. "Returns to Poultry Research in the United States." *Journal of Farm Economics* 49: 656-69.

Phillips, P. 1997. Manual search of ISI Citations Index. July 1997.

Pickett, A. A. and Galwey, P.W. 1997. "A further evaluation of hybrid wheat." *Plant Varieties and Seeds* 10:15-32.

Prairie Pools Inc. 1992-97. *Prairie Grain Variety Survey.* Various Issues.

Ravenscraft, D. and **F.M. Scherer. 1982.** "The Lag Structure of Returns to Research and Development." *Applied Economics* 14(1982): 603-620.

Rose, F. 1980. "Supply Shifts and Research Benefits: Comments." 1980. *American Journal of Agricultural Economics* 62(1980): 834-837.

Rourke, D. R. S. 1986. "Intensive management of wheat in western Canada." p 69-86. *In* Slinkard, A. E. and Fowler, D. B. (eds) *Wheat production in Canada-A Review.* Proceedings of the Canadian Wheat Production Conference. 3-5 March, 1986. Saskatoon, Canada.

Saskatchewan Agriculture and Food. 1997. *Agricultural Statistics.*

Saskatchewan Agriculture and Food. 1969-1997. *Varieties of Grains Crops in Saskatchewan.* Various Issues.

Sears, R. G. 1990. "What does the future hold in wheat breeding." *In Proceedings of MEY Wheat Management Conference.* March 7-9, 1990. Colorado, USA.

Snape, J. W. 1996. "The Contribution of new Biotechnology's to Wheat Breeding." p. 169-181. *In* Reynolds, M. P., Rajaram, S., and McNab, A. (eds) *Increasing Yield Potential in Wheat: Breaking the Barriers.* Proc. Workshop. March 1996. Ciudad Obregon, Sonora, Mexico.

Williams, P. C. 1993. "The World of Wheat." p. 557-602. *Grains & Oilseeds: Handling, Marketing, Processing.* Canadian International Grains Institute. Winnipeg, Manitoba, Canada.

Statistics Canada. 1998a. *Direct Cansim Time Series: CPI and All Goods for Canada.*

Statistics Canada. 1998b. *Direct Cansim Time Series: Canola – Rapeseed/Production, Metric Tonnes, Canola – Canada.*

Thirtle, C.G. and **P. Bottomley. 1988.** "Is Publicly Funded Agricultural Research Excessive?" *Journal of Agricultural Economics* 31:99-111.

Ulrich, A., H. Furtan and **K. Downey. 1984.** "Biotechnology and Rapeseed Breeding: Some Economic Considerations." A Manuscript Report Prepared for the Science Council of Canada.

Ulrich, A.W. and **W.H. Furtan. 1985.** *An Investigation in the Rates of Return from the Canadian Crop Breeding Program.*

Van Kooten, C.G. 1993. *Land Resource Economics and Sustainable Development. Economic Policies and the Common Good.* Vancouver: UBC Press.

Zentner, R.P. 1982. " An Economic Evaluation of Public Wheat Research Expenditures in Canada." PhD Thesis, University of Minnesota.